NATIONAL ENERGY TECHNOLOGY LABORATORY

Life Cycle Analysis: Power Studies Compilation Report

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National Energy Technology Laboratory (NETL), U.S. DOE

October 7, 2010

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Advancing energy options to fuel our economy, strengthen our security and improve our environment

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The Case for Life Cycle View of Power

- **Environmental impacts of electricity generation occur at the power plant**
  - In 2005, 30% of U.S. greenhouse gas emissions came from coal combustion (for power) (EIA, 2005)
- **Regulation and technology are reducing those impacts**
  - Flue Gas Desulfurization for SOX
  - Selective Catalytic Reduction for NOX
  - Electrostatic Precipitators for Particulates
  - Carbon Capture & Sequestration for CO_2
- **As this happens, the *relative* impact from other stages of power production gets larger**

The Case for Life Cycle View of Power

- **To accurately account for and compare impacts from these different forms of power production, we need an inventory for each at every stage of their life cycle**

LC Stage #1
Raw Materials Acquisition
(RMA)

→

LC Stage #2
Raw Materials Transport
(RMT)

→

LC Stage #3
Energy Conversion Facility
(ECF)

→

LC Stage #4
Power Transmission
(PT)

→

LC Stage #5
End Use

- **The tool we use for this accounting is life cycle assessment or LCA**
  - For each stage, we perform mass and energy balances of the processes it contains
  - There can be a single process per stage, or multiple, including construction, operations and decommissioning

The Life Cycle Inventory, Impacts and Costing

- **At NETL, our inventory is comprehensive, and includes:**
  - Greenhouse gases (CO_2, CH_4, N_2O, SF_6)
  - Criteria Air Pollutants (CO, SO_x, NO_x, PM)
  - Toxic Materials (Hg, Pb)
  - Land Use
  - Water use

- **We do not convert these inventories into impact (such as effect on the ecosystem or human health), with one exception**
  - We convert greenhouse gas inventories into Global Warming Potential (GWP)
  - GWP is measured in 100-year CO_2 Equivalents (CO_2e), using 2007 IPCC conversions

- **We include a traditional life cycle cost (LCC) analysis of each technology pathway as well**

The Power LCA Studies

- **This report compiles the results from four technology life cycle assessments**
  1. Integrated Gasification Combined Cycle (IGCC)
  2. Natural Gas Combined Cycle from Liquefied Natural Gas (NGCC-LNG)
  3. Super Critical Pulverized Coal (SCPC)
  4. Existing Sub-Critical Pulverized Coal with Retrofit (EXPC)
- **Each case was modeled without and with Carbon Capture and Sequestration (CCS)**

Approach: The Importance of Assumptions

- **One of the main benefits of LCA is the ability to compare different technologies across a common denominator, or, in LCA terms, functional unit**
  - Our functional unit for these studies is 1 MWh of electricity delivered to the end user
- **When comparing systems this complex, it's never quite that easy**
  - The plants need to perform similar roles, e.g. baseload generation
  - Need to exist in locations which give fair access to resource and infrastructure
  - New technology and infrastructure needs to be fairly compared to existing
- **The assumptions made to ensure comparability on the basis of our functional unit can drive results, so we perform uncertainty and sensitivity analysis on important assumptions**

Major Data Sources

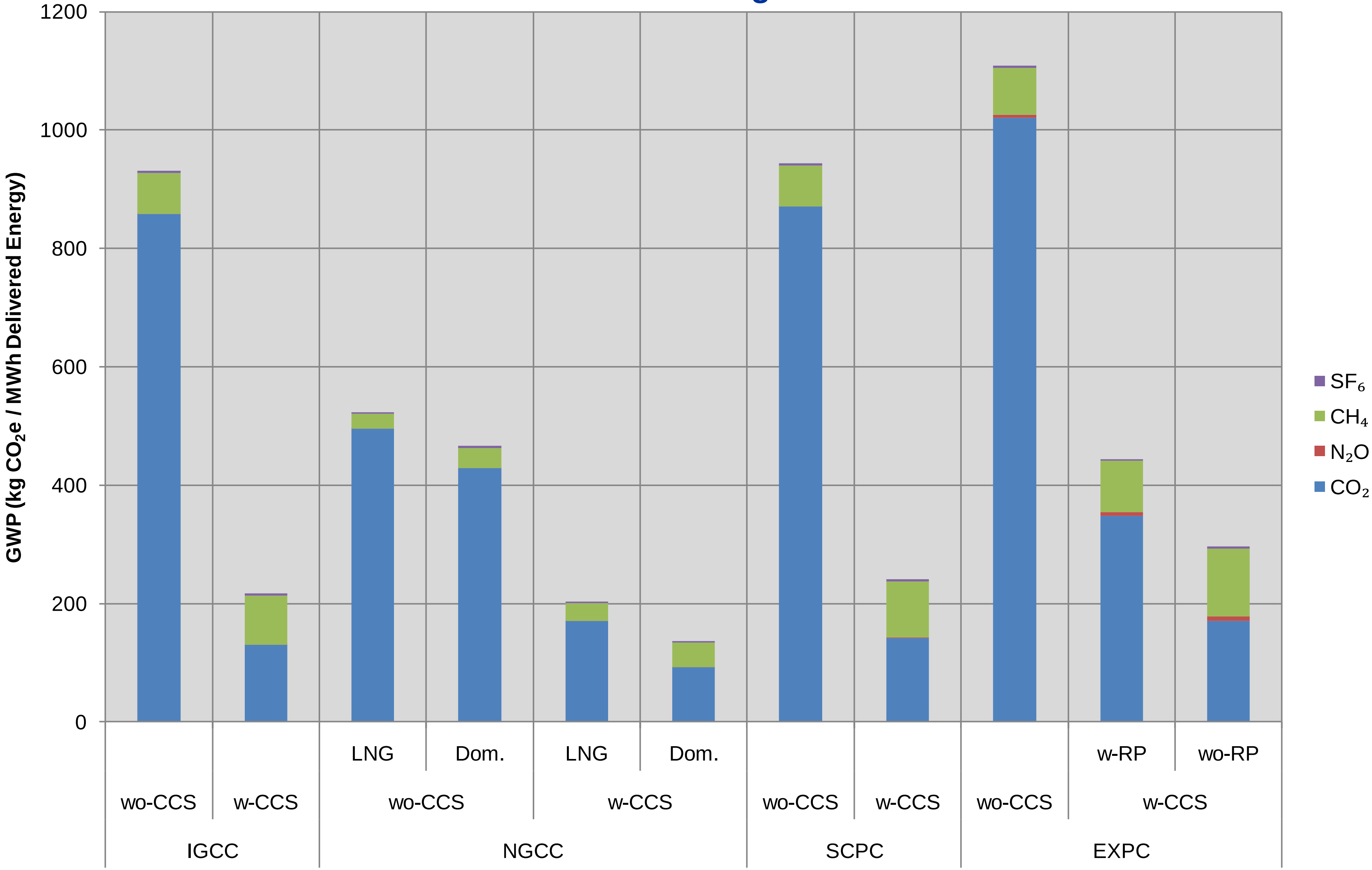
- **Power LCA Builds Upon the Following NETL Techno-economic Analysis Studies:**
  - *Cost and Performance Baseline for Fossil Energy Plants; Volume I (Bituminous Coal and Natural Gas to Electricity)*; Revision Expected October 2010
  - *Carbon Dioxide Capture from Existing Coal-Fired Power Plants*; November 2007 http://www.netl.doe.gov/energy-analyses/refshelf/PubDetails.aspx?Action=View&PubId=225

Key Modeling Assumptions

Assumptions	IGCC	NGCC-LNG		SCPC	EXPC
		Foreign Liquified Natural Gas (LNG)	Domestic Natural Gas (DNG)		
Temporal / Cost Boundary	30 Years / Overnight				
LC Stage #1: Raw Material Acquisition					
Extraction Location	Southern Illinois	Trinidad & Tobago	Domestic Onshore/Offshore	Southern Illinois	Southern Illinois
Feedstock	Ill. #6 Coal	LNG	NG	Ill. #6 Coal	Ill. #6 Coal
Extraction Method	Underground	Offshore Drilling	Multiple Pathway	Underground	Underground
C&O Costs	In Delivery Price				
LC Stage #2: Raw Material Transport					
One-way transport Distance (Miles)	1170	4520	NA	410	400
Rail Spur Length (Miles)	25	NA		25	Pre-Existing
Main Rail/Pipeline Length (Miles)	Pre-Existing	208	900	Pre-Existing	Pre-Existing
C&O Costs	In Delivery Price				
LC Stage #3: Energy Conversion Facility					
Location	Southern Mississippi			Southern Illinois	
Net Output (MW)	622	555		550	434
Net Output w-CCS (MW)	543	474		550	NA
Net Output w-CCS with Replacement Power (w-RP) (MW)	NA				434
Net Output w-CCS without Replacement Power (wo-RP) (MW)	NA				303
Capacity Factor	80%	85%			
Trunk line Constructed Length (Miles)	50				Pre-Existing
CO_2 Capture Rate	90%				
CO_2 Pipeline Pressure (psia)	2215				
CO_2 Pipeline Length (Miles)	100				
CO_2 Loss Rate	1% / 100 yrs				
LC Stage #4: Product Transport					
Transmission Line Loss	7%				
Transmission Grid Construction	Pre-Existing				

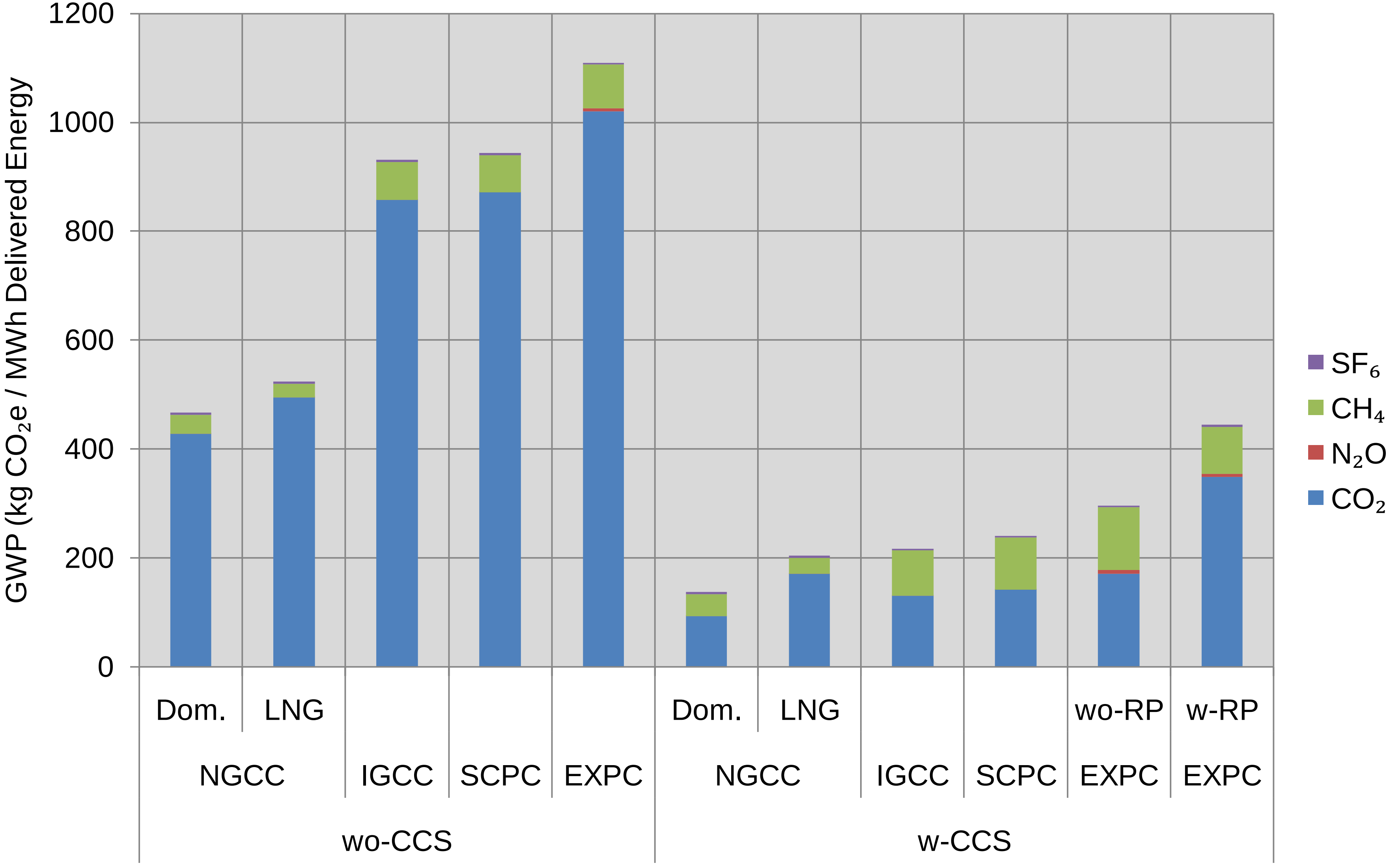
Life Cycle GHG Emissions

Affect of Adding CCS



Life Cycle GHG Emissions

Technology Comparison – Without and With CCS



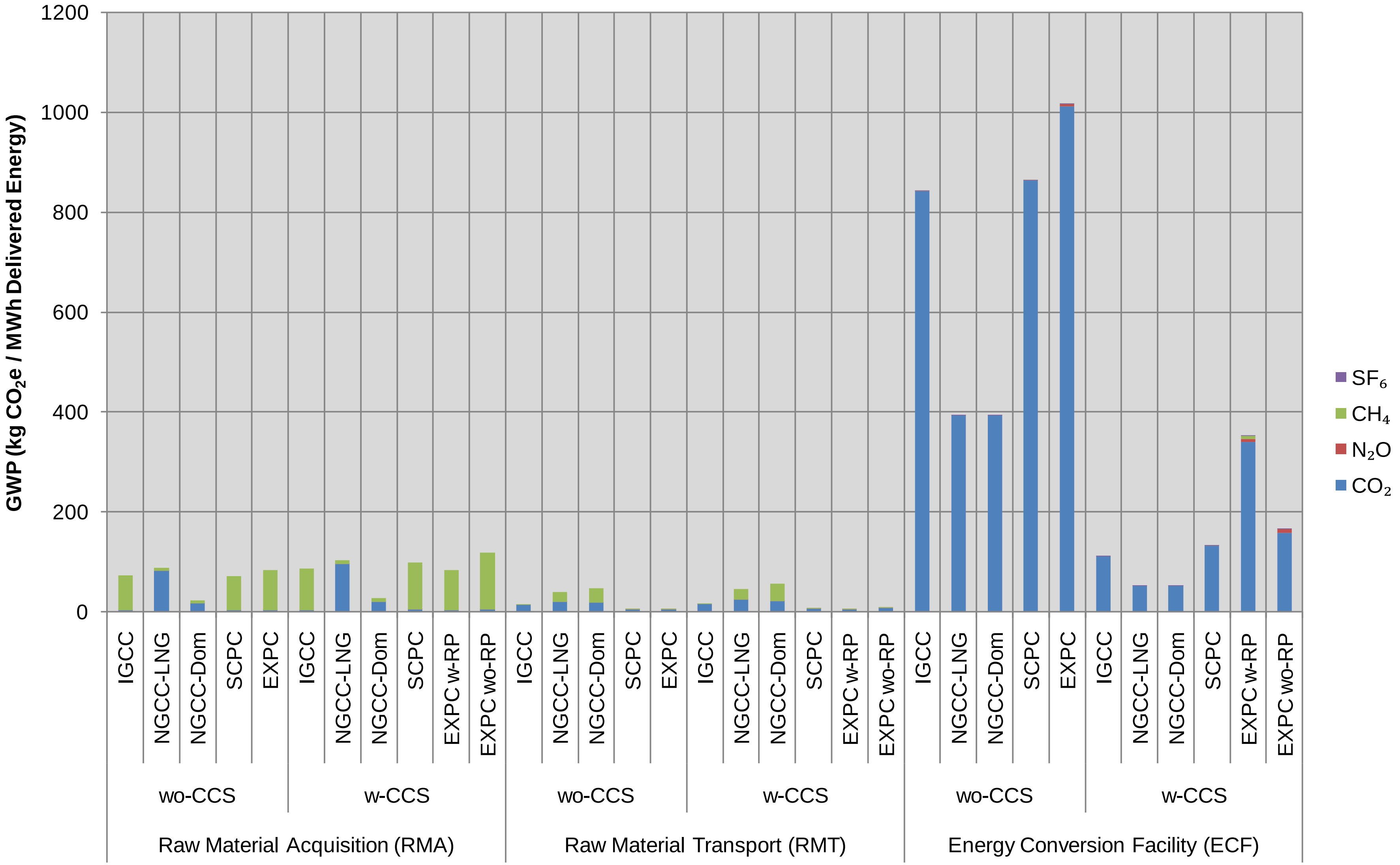
Life Cycle GHG Emissions

Tabular Data

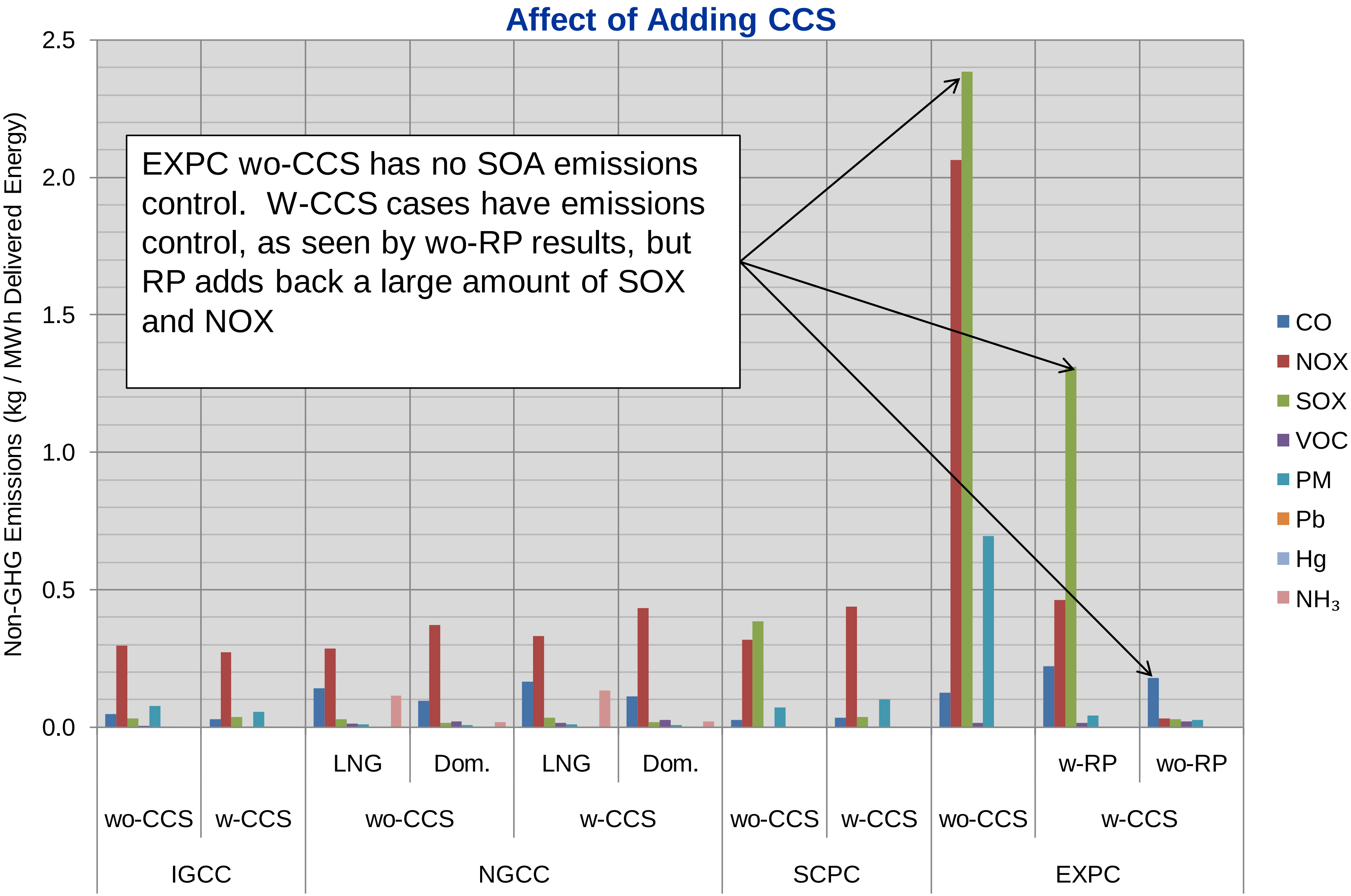
Species	IGCC		NGCC				SCPC		EXPC		
	wo-CCS	w-CCS	wo-CCS		w-CCS		wo-CCS	w-CCS	wo-CCS	w-CCS	
			LNG	Dom.	LNG	Dom.				w-RP	wo-RP
CO_2	857.90	130.48	494.98	428.11	170.80	92.41	871.25	142.18	1020.17	348.37	170.35
N_2O	0.03	0.04	0.20	0.11	0.23	0.14	0.03	0.04	5.18	6.08	7.45
CH_4	69.75	83.32	25.20	35.13	29.54	41.18	68.93	95.24	80.32	86.50	115.03
SF_6	3.27	3.28	3.28	3.28	3.28	3.28	3.28	3.28	3.20	3.20	3.20
Total	**930.95**	**217.12**	**523.65**	**466.63**	**203.84**	**137.00**	**943.49**	**240.73**	**1108.87**	**444.15**	**296.03**

Life Cycle GHG Emissions

Stage-by-Stage Results – Without and With CCS



Life Cycle Non-GHG Air Emissions



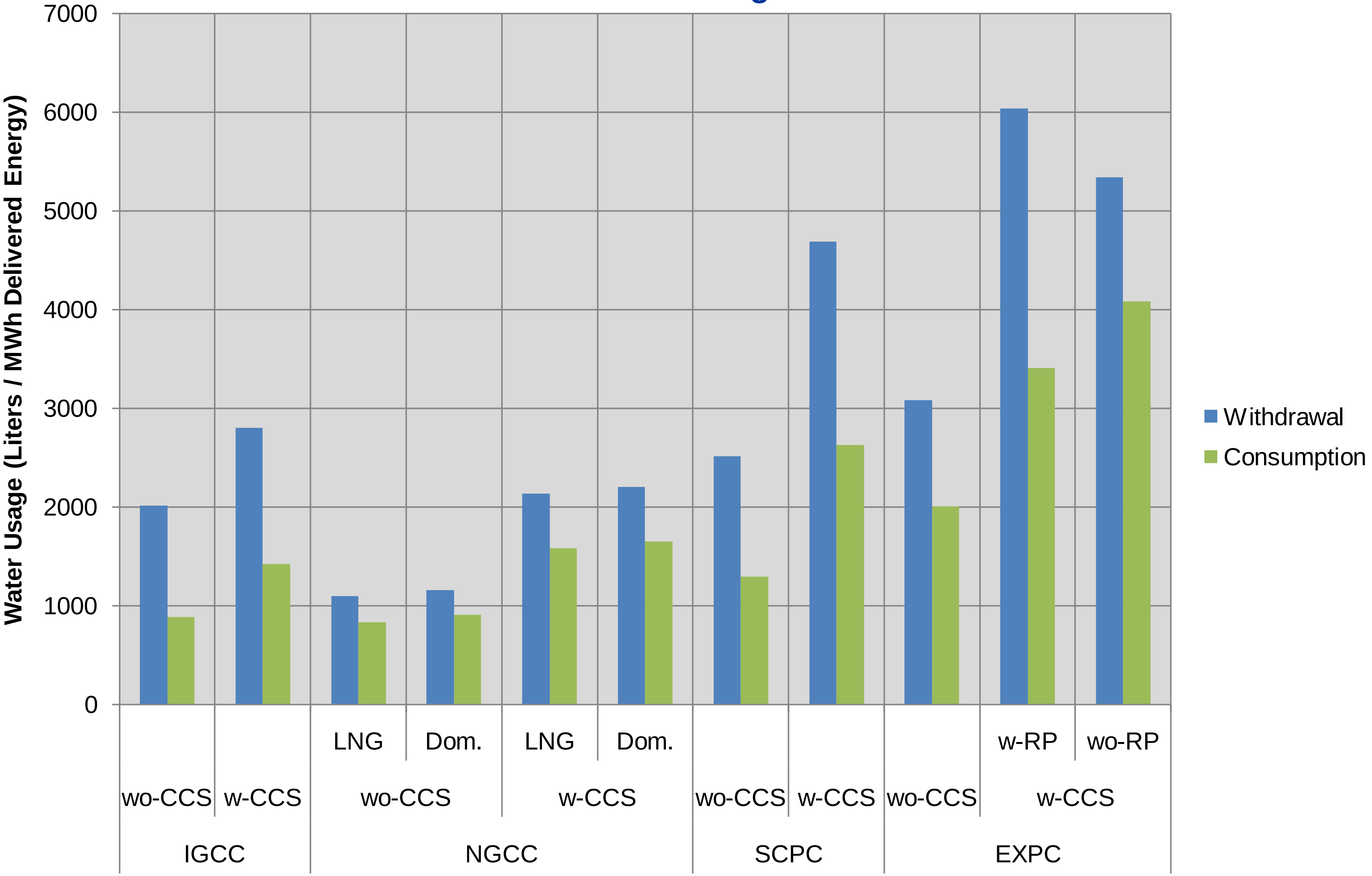
Life Cycle Non-GHG Air Emissions

Tabular Data

Species	IGCC		NGCC				SCPC		EXPC		
	wo-CCS	w-CCS	wo-CCS		w-CCS		wo-CCS	w-CCS	wo-CCS	w-CCS	
			LNG	Dom.	LNG	Dom.				w-RP	wo-RP
CO	0.048	0.030	0.141	0.095	0.166	0.112	0.025	0.034	0.125	0.221	0.178
NOX	0.296	0.273	0.285	0.370	0.332	0.432	0.317	0.438	2.063	0.464	0.033
SOX	0.030	0.035	0.029	0.014	0.034	0.017	0.384	0.038	2.384	1.310	0.029
VOC	0.004	0.002	0.014	0.021	0.016	0.025	0.002	0.002	0.014	0.014	0.020
PM	0.076	0.056	0.009	0.006	0.011	0.007	0.072	0.100	0.695	0.043	0.026
Pb	1.34E-05	1.67E-05	4.63E-06	3.43E-06	5.34E-06	3.93E-06	4.58E-05	4.68E-05	6.51E-06	1.89E-05	1.00E-05
Hg	2.44E-06	2.82E-06	1.52E-07	5.94E-08	1.85E-07	7.58E-08	4.54E-06	7.25E-06	5.17E-05	5.49E-05	7.43E-05
NH_3	5.04E-04	2.29E-04	1.16E-01	1.88E-02	1.34E-01	2.03E-02	2.58E-03	3.01E-03	4.30E-04	1.51E-03	6.22E-04

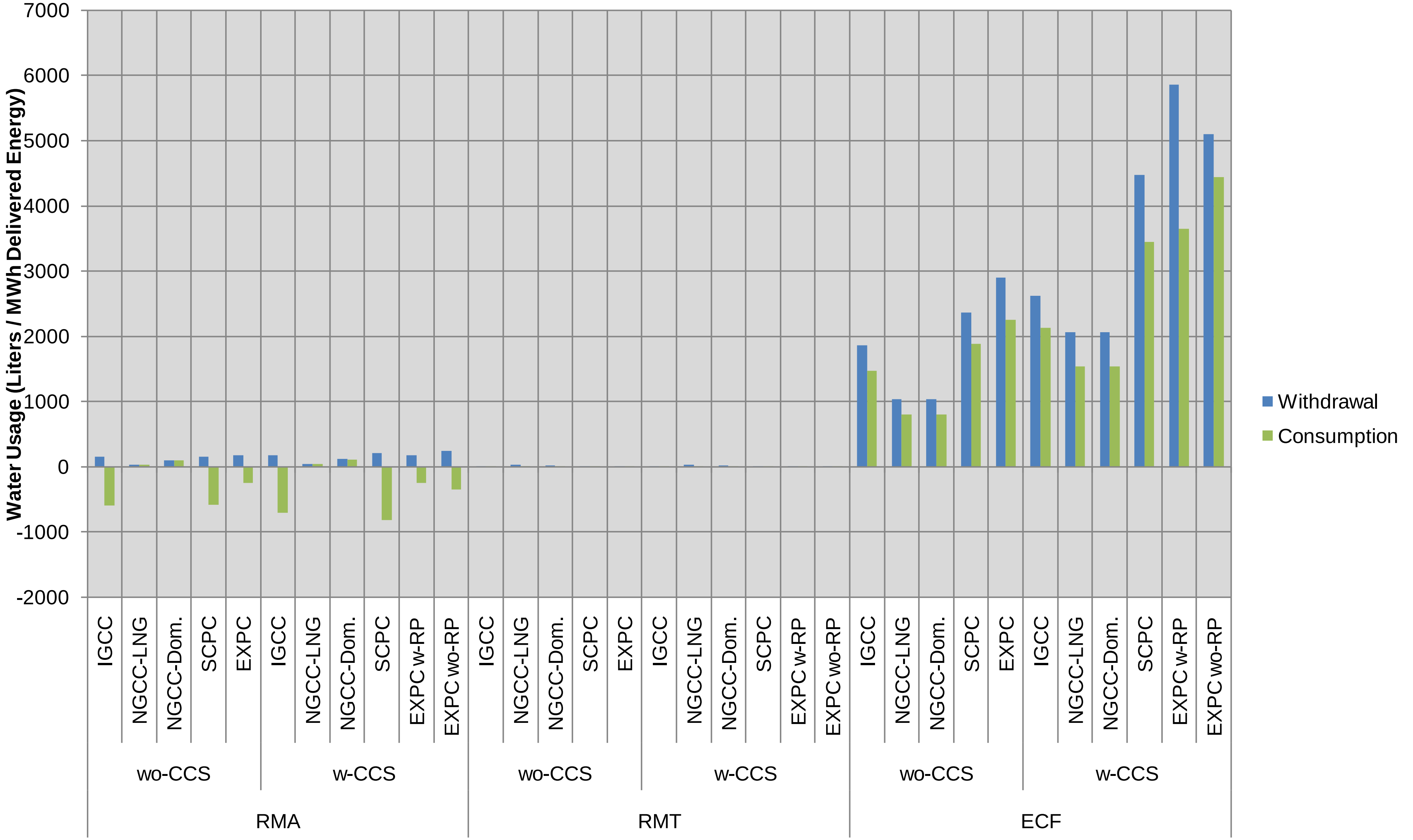
Life Cycle Water Usage

Affect of Adding CCS



Life Cycle Water Usage

Stage-by-Stage – Without and With CCS



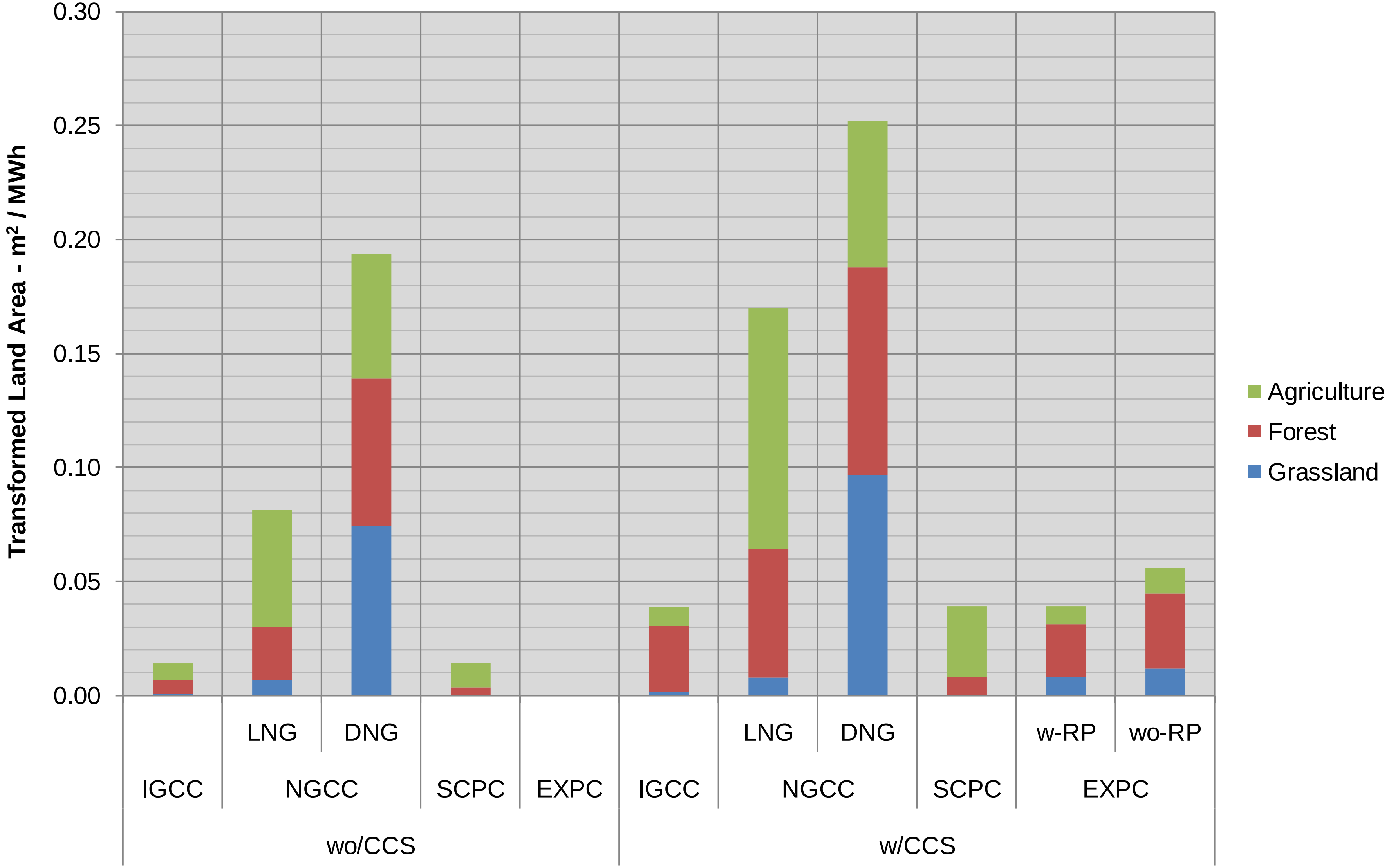
Life Cycle Water Usage

Tabular Data

Parameter	IGCC		NGCC				SCPC		EXPC		
	wo-CCS	w-CCS	wo-CCS		w-CCS		wo-CCS	w-CCS	wo-CCS	w-CCS	
			LNG	Dom.	LNG	Dom.				w-RP	wo-RP
Input	2013.90	2803.21	1098.61	1155.11	2133.49	2199.72	2515.02	4687.91	3078.61	6037.86	5343.11
Output	1132.04	1380.42	266.46	245.54	551.33	548.58	1223.29	2057.23	1075.35	2631.28	1256.90
Consumption	881.86	1422.79	832.15	909.57	1582.16	1651.14	1291.72	2630.68	2003.26	3406.58	4086.21

Transformed Land Area

Affect of Adding CCS



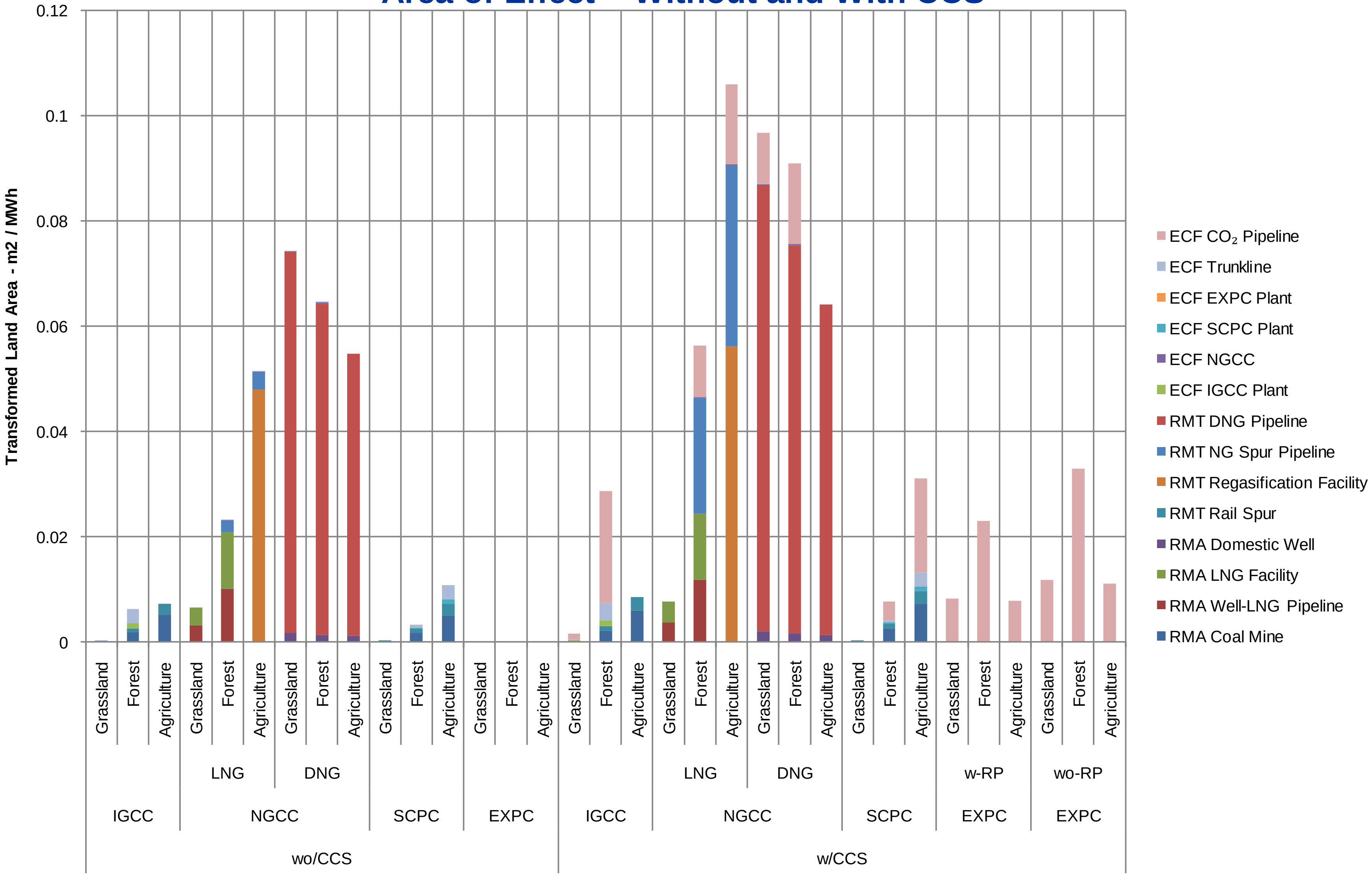
Transformed Land Area

Tabular Data

Land Use Type	wo/CCS					w/CCS					
	IGCC	NGCC		SCPC	EXPC	IGCC	NGCC		SCPC	EXPC	
		LNG	DNG				LNG	DNG		w-RP	wo-RP
Grassland	3.97E-04	6.61E-03	7.44E-02	2.03E-04	0.00E+00	1.59E-03	7.74E-03	9.68E-02	2.68E-04	8.24E-03	1.18E-02
Forest	6.34E-03	2.32E-02	6.47E-02	3.34E-03	0.00E+00	2.88E-02	5.63E-02	9.10E-02	7.78E-03	2.30E-02	3.30E-02
Agriculture	7.25E-03	5.15E-02	5.48E-02	1.08E-02	0.00E+00	8.50E-03	1.06E-01	6.41E-02	3.12E-02	7.80E-03	1.12E-02

Transformed Land Area

Area of Effect – Without and With CCS

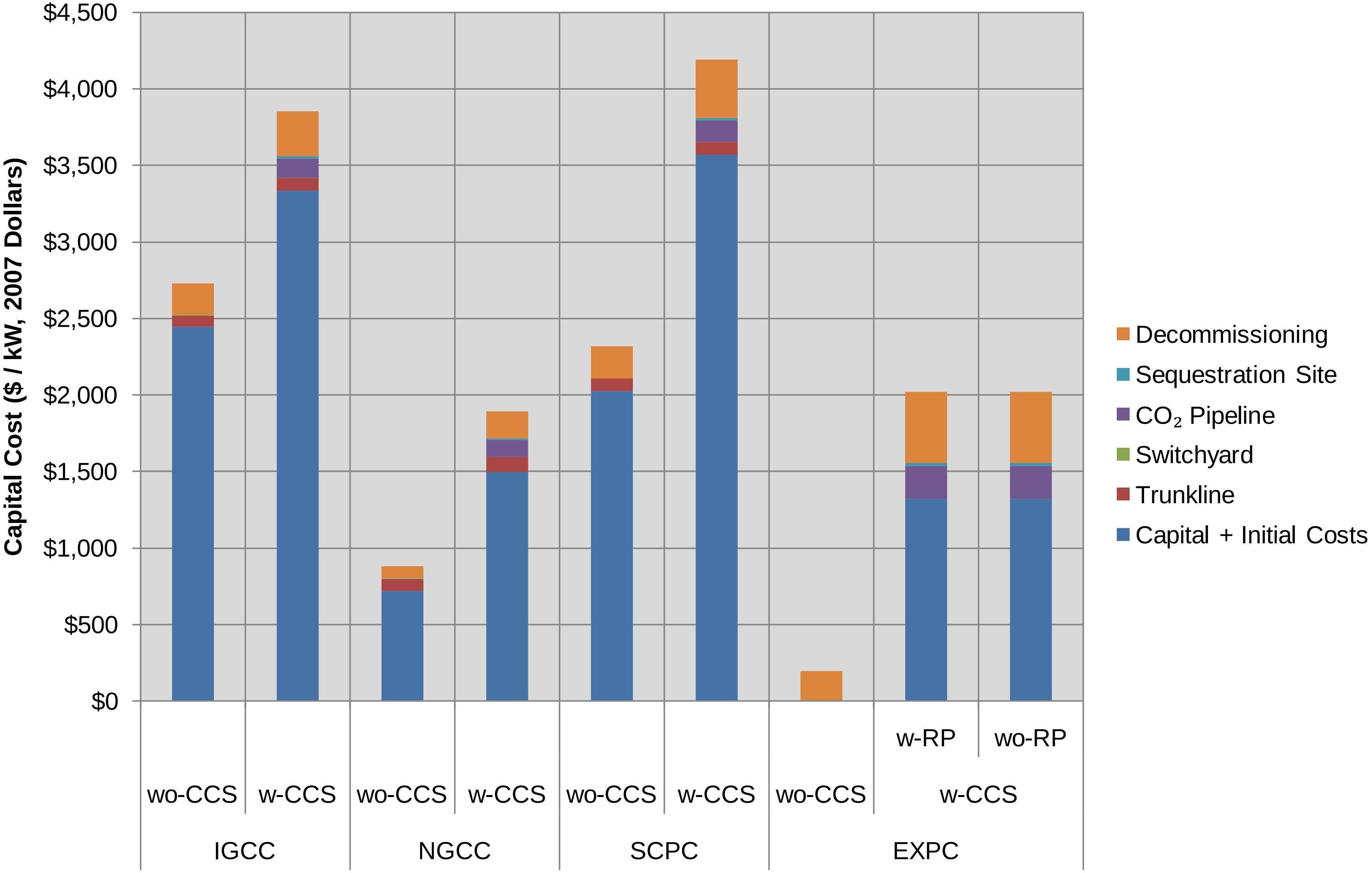


Financial Parameters

Property	Value	Units
Reference Year Dollars	December 2006/January 2007	Year
Assumed Start-Up Year	2010	Year
Real After-Tax Discount Rate	10.0	Percent
After-Tax Nominal Discount Rate	12.09	Percent
Assumed Study Period	30	Years
MACRS Depreciation Schedule Length	Variable	Years
Inflation Rate	1.87	Percent
State Taxes	6.0	Percent
Federal Taxes	34.0	Percent
Total Tax Rate	38.0	Percent
Start Up Year (2010) Feedstock & Utility Prices	***$2007 Dollars***	**Units**
Natural Gas	6.76	$/MMBtu
Coal	1.51	$/MMBtu
Process Water	0.00049 (0.0019)	$/L ($/gal)

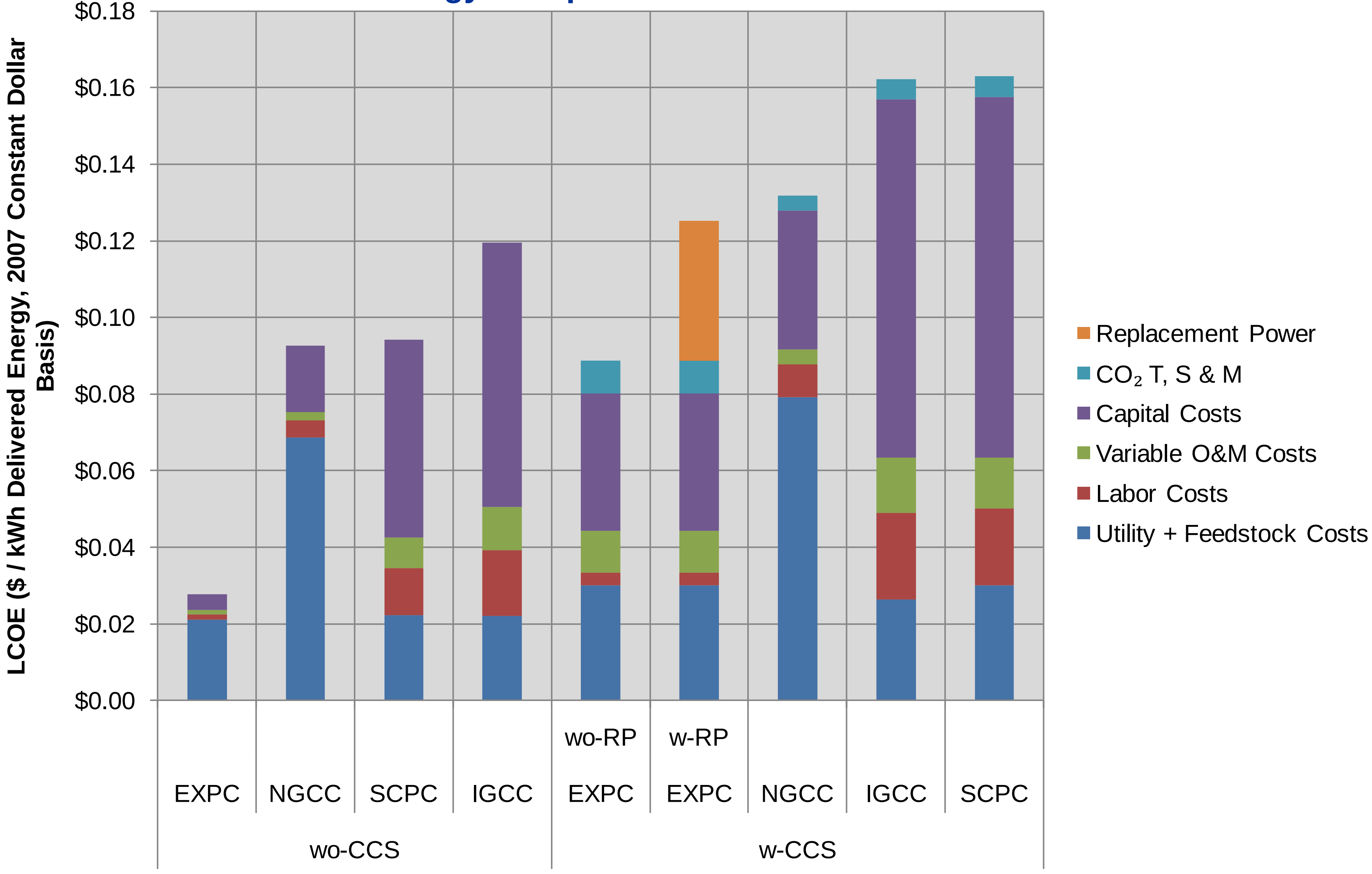
Life Cycle Capital Cost

Affect of adding CCS



Life Cycle Capital Cost

Technology Comparison - Without and With CCS



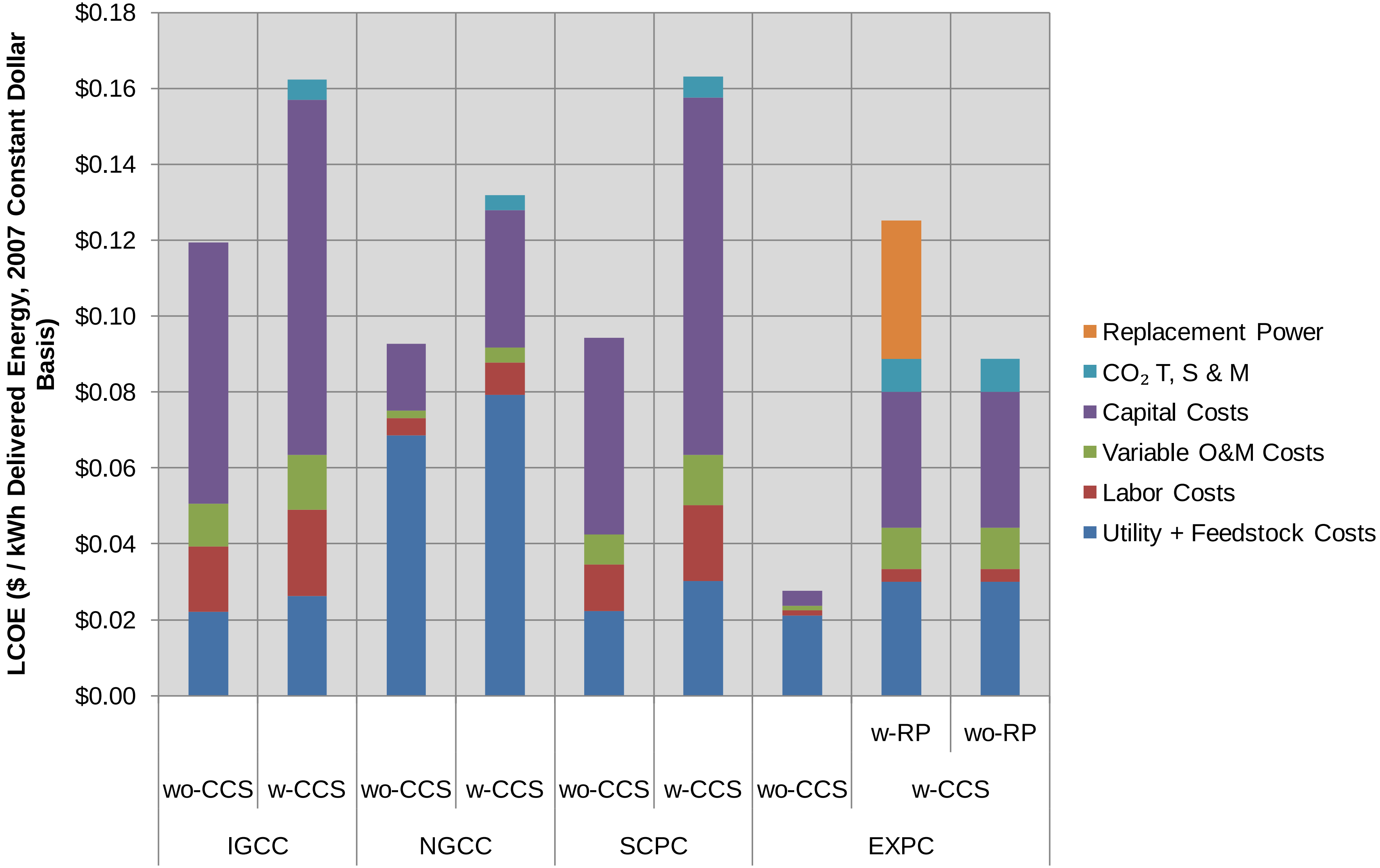
Life Cycle Capital Cost

Tabular Data

Parameter	wo-CCS				w-CCS				
	EXPC	NGCC	SCPC	IGCC	NGCC	EXPC		IGCC	SCPC
						w-RP	wo-RP		
Capital + Initial Costs	0.00	717.54	2024.48	2446.44	1497.22	1320.44	1320.44	3334.40	3570.46
Trunkline	0.00	82.13	82.89	73.29	96.27	0.00	0.00	83.92	82.89
Switchyard	0.00	1.87	1.89	1.67	2.20	0.00	0.00	1.91	1.89
CO_2 Pipeline	0.00	0.00	0.00	0.00	109.61	215.85	215.85	127.21	140.04
Sequestration Site	0.00	0.00	0.00	0.00	13.09	20.46	20.46	14.17	14.00
Decommis-sioning	196.45	80.15	210.83	206.18	172.51	462.79	462.79	294.66	381.69
Total	196.45	881.70	2320.10	2727.57	1890.89	2019.55	2019.55	3856.27	4190.97

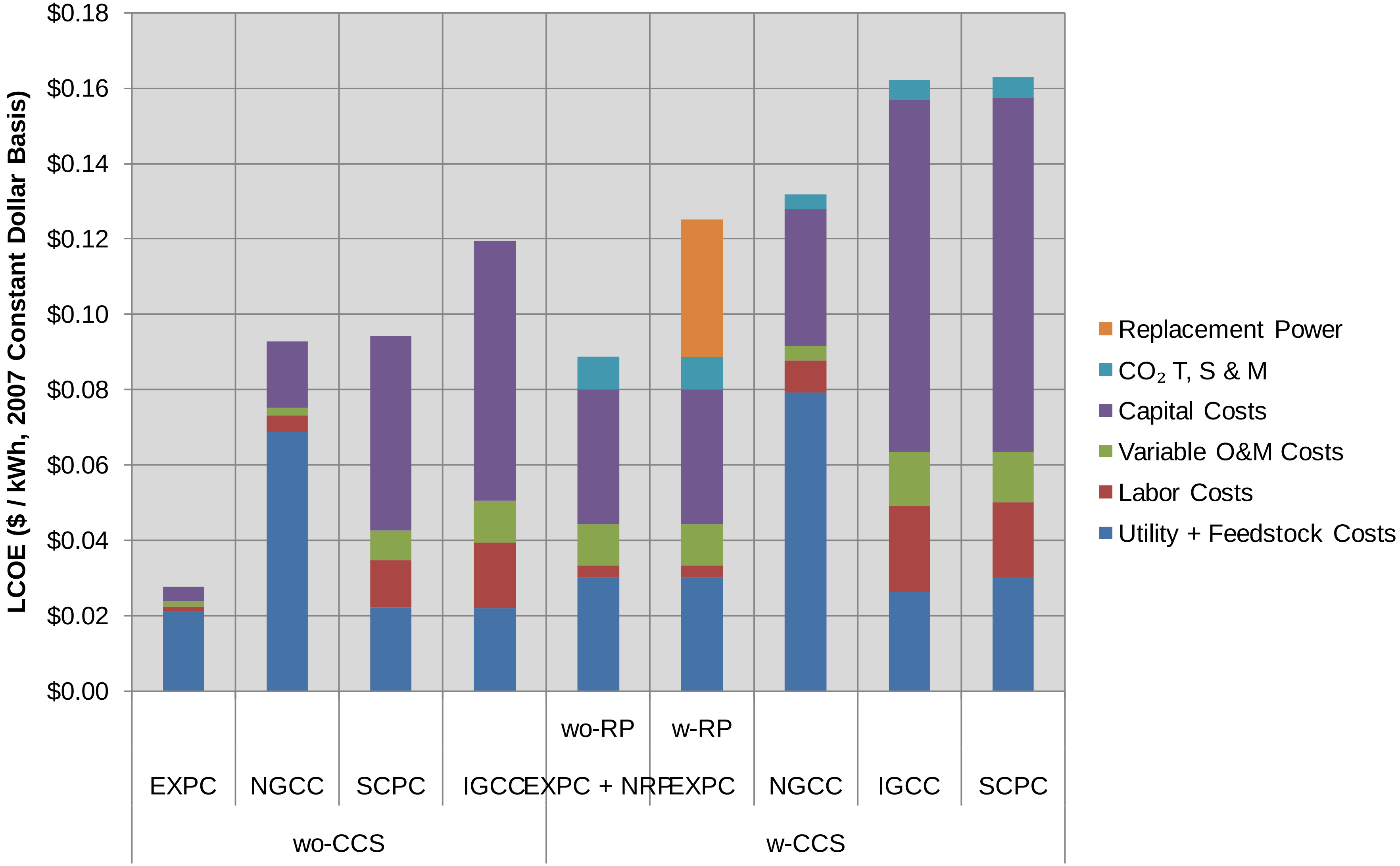
LCOE

Affect of adding CCS



LCOE

Technology Comparison – Without and With CCS



LCOE

Tabular Data

Parameter	wo-CCS				w-CCS				
	EXPC	NGCC	SCPC	IGCC	EXPC	EXPC	NGCC	IGCC	SCPC
					wo-RP	w-RP			
Utility + Feedstock Costs	$0.0211	$0.0686	$0.0222	$0.0220	$0.0301	$0.0301	$0.0792	$0.0263	$0.0302
Labor Costs	$0.0013	$0.0046	$0.0124	$0.0173	$0.0032	$0.0032	$0.0086	$0.0227	$0.0199
Variable O&M Costs	$0.0013	$0.0020	$0.0079	$0.0112	$0.0109	$0.0109	$0.0039	$0.0143	$0.0134
Capital Costs	$0.0040	$0.0175	$0.0518	$0.0690	$0.0359	$0.0359	$0.0363	$0.0936	$0.0941
CO_2 T, S & M	$0.0000	$0.0000	$0.0000	$0.0000	$0.0086	$0.0086	$0.0039	$0.0053	$0.0054
Replacement Power	$0.0000	$0.0000	$0.0000	$0.0000	$0.0000	$0.0365	$0.0000	$0.0000	$0.0000
Total LC LCOE	$0.0277	$0.0927	$0.0943	$0.1195	$0.0887	$0.1252	$0.1319	$0.1622	$0.1630

Key Findings for GHG Footprint

GWP (CO_2e) – 2007 IPCC 100 yr. Average

- **CO_2**
  - CO_2 makes up 95-99% of the GHG emissions from Energy Conversion Facility Stage for all Technologies
  - CO_2 makes up between 58-95% of overall GHG Emissions for all Technologies
  - The other major source of CO2 is from Foreign Drilling operations
    - 16% wo-CCS and 47% w-CCS of Total GHG Emissions for LNG
- **Methane**
  - The major source of methane emissions comes from the RMA Stage of the Coal Cases
    - Coal Bed Methane makes up 96% of GHG Emissions from the RMA Stage
    - Methane from the RMA Stage makes up 99% of overall Methane emissions
      - EXPC w-RP is slightly lower (92%) due to the SERC power mix
  - NG Cases – Highest percentages from RMT
    - Foreign LNG Regasification accounts for 75-81% of the overall Methane emissions
    - Pipeline operation in the RMA Stage results in 25% of overall Methane emissions for LNG, and 18% for DNG

Key Findings for GHG Footprint (Cont.)

GWP (CO_2e) – 2007 IPCC 100 yr. Average

- **Addition of CCS with a 90% CO_2 Capture system results in an overall Life Cycle GHG reduction of:**
  - IGCC – 77% Reduction
  - NGCC – 61% Reduction for LNG, 70% for DNG
  - SCPC – 75% Reduction
  - EXPC – 60% Reduction
- **EXPC**
  - Replacement Power for the EXPC w-CCS case adds 50% to the total GHG Emissions
    - Due to the Average Emissions Profile of the SERC Region of Power Units
- **Overall Domestic NG GHG Emissions are less than Foreign LNG GHG Emissions**
  - Domestic NG wo-CCS is 12% lower than Foreign LNG wo-CCS
  - Domestic NG w-CCS is 48% lower than Foreign LNG w-CCS
  - Expected more of difference between DNG and LNG

Key Findings – Non-GHG Emissions

- **NOX was found to be the dominant Non-GHG emission for all cases**
  - Exceptions to the rule were SCPC wo-CCS, and the EXPC Cases
- **SOX was the dominant species of emission in SCPC and EXPC wo-CCS**
  - The SCPC and EXPC w-CCS cases used Amine process for CO_2 removal, which required an extra gas polishing step which removed SOX to 15 ppmv
  - In the EXPC w-CCS w-RP, an increase in SOX was seen, due to emissions related to the Replacement Power
- **Particulate Matter was seen primarily in the Coal cases only, yielding an emission due to Fugitive Dust from Coal transport in the RMT Stage**
- **Ammonia typically less than 1% of the NOX emissions, except for the NGCC Cases:**
  - Selective Catalytic Reduction Unit ammonia slip resulted in ammonia release that was 5% of the NOX emissions
  - Ammonia Emissions from the Liquefaction plant for Foreign LNG amounted to an ammonia emissions that were 40% of the NOX emissions

Key Findings – Water Usage

- **Energy Conversion Facility**
  - The ECF stage is the primary water user in all technologies
  - Input and Consumption vary between 88 - 97% for the ECF
- **Coal Cases**
  - There is a net production of water at the Mine
    - Due to Site Stormwater & Mine Runoff
  - This net production affects the overall Consumption
    - The total LC Consumption is less than consumption at the ECF – due to the offset
- **Domestic NG versus Foreign LNG**
  - There is a 3 - 5% increase overall water consumption for DNG
- **CCS**
  - There is an increase in water input and consumption for all technologies
  - This is due to increased cooling load needed for operation of the CCS systems

Key Findings – Life Cycle Capital Cost

- **Capital Equipment Costs**
  - Bare Erected Equipment cost accounts for 79 - 90% of the Life Cycle Capital Cost
  - EXPC
    - For the wo-CCS case, the only cost attributed to Capital Cost is decommissioning
    - For the w-CCS case, 65% of Capital Cost is due to bare equipment cost
    - When switching from with to without Replacement Power there is no Capital Cost added to the system
      - Replacement Power is dealt with as a purchased quantity, affecting the LCOE
- **CCS**
  - The addition of the CCS system to each technology increases Capital Cost between 40 - 80%
  - Addition of CCS to the EXPC systems registers a 930% increase in Capital Cost
    - Recall that the wo-CCS Capital Cost included only Decommissioning
    - In reality, the increase in Capital Cost is almost equal to that seen by the SCPC system

Key Findings - LCOE

- **Coal Cases (IGCC and SCPC)**
  - Capital Costs are the largest component of the LCOE composite number for each technology
    - Capital Costs range between 30 – 56% of the overall value of the LCOE
- **NG Cases**
  - Utility Costs are the largest component of the LCOE composite number for the NG cases
    - Utility costs range between 60 – 74% of the overall value of the LCOE
- **CCS**
  - Addition of CCS to the Technologies increased the LCOE between 36 - 75%
- **EXPC**
  - When factoring in the cost of the Replacement power for the with CCS cases
    - The case with Replacement power shows a 350% increase in LCOE
    - The case without Replacement power shows a 220% increase in LCOE

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